Final Report

ADDITIONAL BEAM PARAMETER MEASUREMENTS AND COMPLETION OF AN ATOMIC BEAM SYSTEM

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ABSTRACT

A Neutral Beam Apparatus has been built for the Goddard Space Flight Center for the purposes of studying the effects of medium energy neutral particles on upper atmospheric sensors and test surfaces. The apparatus consists of an atomic beam source, a source chamber, a velocity selector, a torsion balance and ancillary electronics and pumps. Testing has been carried out and the system was installed at Goddard Space Flight Center.

Sputter acceleration studies with oxygen and nitrogen were made for bombardment voltages from 500 volts to 5000 volts. Forces for the total beam flux were obtained of $\sim 10^{-2}$ dynes/cm^2, representing a neutral particle flux of $\sim 10^{17}$ atoms/cm^2 sec. The velocity selected beam measurements indicated that the average particle energy was above the 10^6 cm/sec velocity capability of the selector; however, selected fluxes of monoenergetic beams were obtained with densities of 3 to 8 x 10^{13} particles/cm^2 sec.

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I. INTRODUCTION

This report discusses the experimental work performed in a program of equipment development for the Goddard Space Flight Center. It is related to a previous program aimed at the generation and investigation of medium energy neutral atomic beams (NAS5-9083), as a means of simulating the bombardment experienced by spacecraft instrumentation from low energy (1 to 10 eV) neutral atoms.

A major objective of the present program was to measure momentum transfer from such beams using a torsion balance technique as a means of beam calibration. The earlier program was hampered by the lack of an absolute measurement technique for determining the number density of the beam. The present effort was aimed at correcting this deficiency as well as to improve beam detection sensitivity. The latter task is accomplished by altering the velocity selector so as to broaden the velocity window observed at any one velocity setting. Upon completion of the program the equipment constructed was supplied to the Goddard Space Flight Center, where it was installed and set in operation. Under the contract an instrument manual is provided for operation and maintenance of the neutral beam system.

II. METHOD OF APPROACH

The method of approach in this contract was principally the design and construction of special torsion balances, which were used to measure momentum transfer in the beam. Quartz torsion balances with atomic traps were used as the detecting medium. In addition, the contract monies were used to improve construction of certain of the atomic beam components and to improve system operation and testing.

Other special modifications were made in the beam system. New velocity selector disks were designed and placed in operation which provided an energy spread in the velocity selection of 10% as opposed to the original 2% previously used. This modification in velocity selection accuracy was accomplished by reducing the number of teeth in the selector, hence, allowing wider side bands to pass. The main chamber was disassembled and the new flanges for the quartz balance and ionization tube were heliarc welded into place and the whole system reassembled into operating form.

Other added components include a new liquid nitrogen cold trap for the crystal mount. This cold trap is now suspended on a stainless steel diaphragm so that the crystal may be turned to the side or up and down through $\pm 5^{\circ}$ with respect to the axis of the beam. The cold trap was constructed so that there is an air outlet right at the back of the crystal surface which provides better liquid nitrogen venting to insure maximum cooling to the crystal. The in-vacuum angle adjustment of the crystal holder is secured to one end of the glass cylinder vacuum chamber.

A new gas inlet has been constructed to feed the nitrogen and oxygen directly into the plasma region so that the gas discharge is confined about the crystal surface. A "floating gate" has been installed on the top of the beam tank which can be used to block or deflect the beam. A metastable quenching panel has also been installed in the beam. When a high potential is placed on the panel the metastable population of the beam can be reduced.

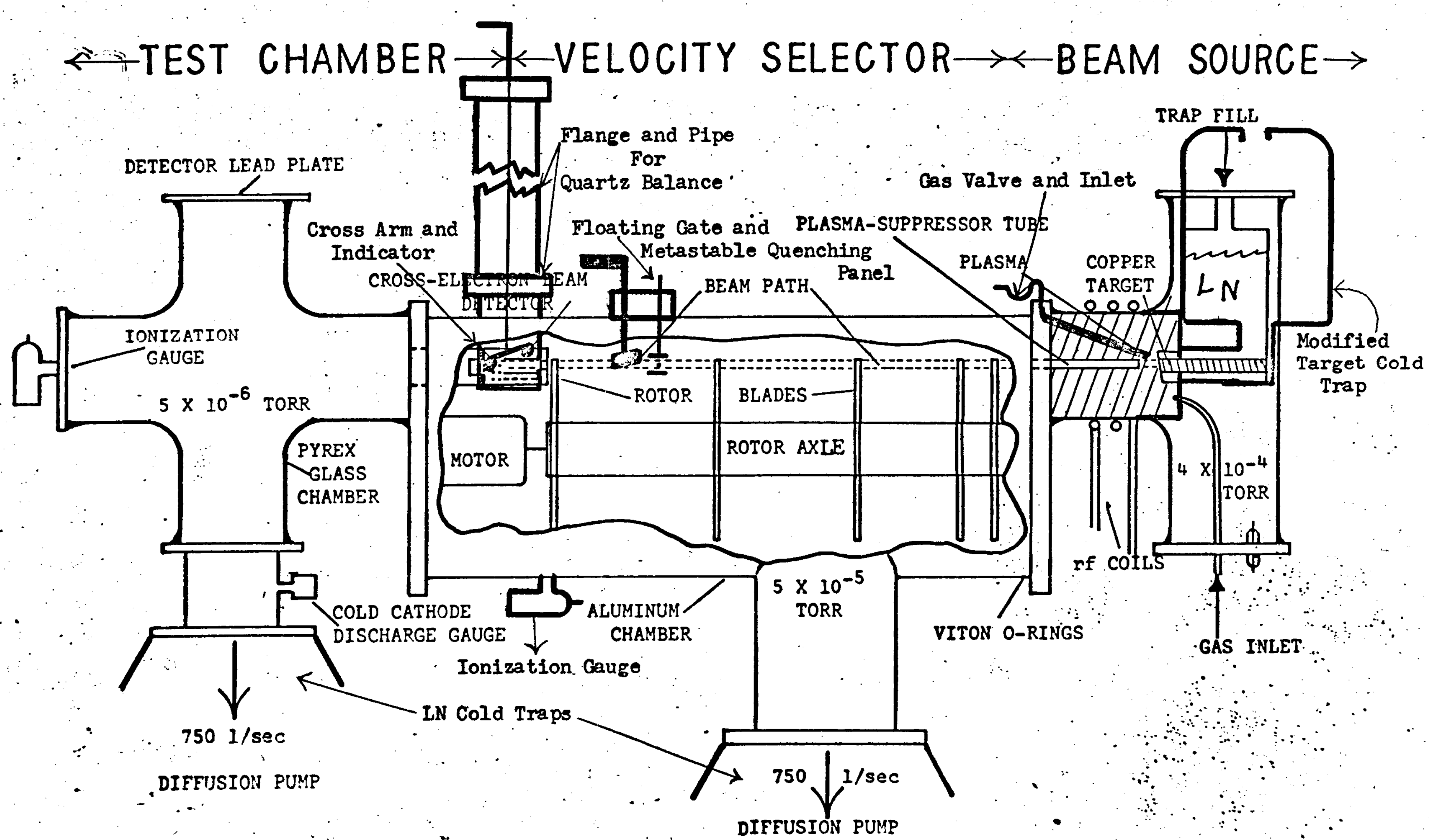
The test stand with water cooling, drain, and r. f. shielding has been reconstructed and put into a form which is more permanent. Additional auxiliary electronics have also been built into the system.

A 5000Vdc - 200 mA power supply was designed and built for the system. This power supply is used as the main ion bombardment control of the cold finger target.

The following additions and modifications summarize the changes made in the equipment under this contract:

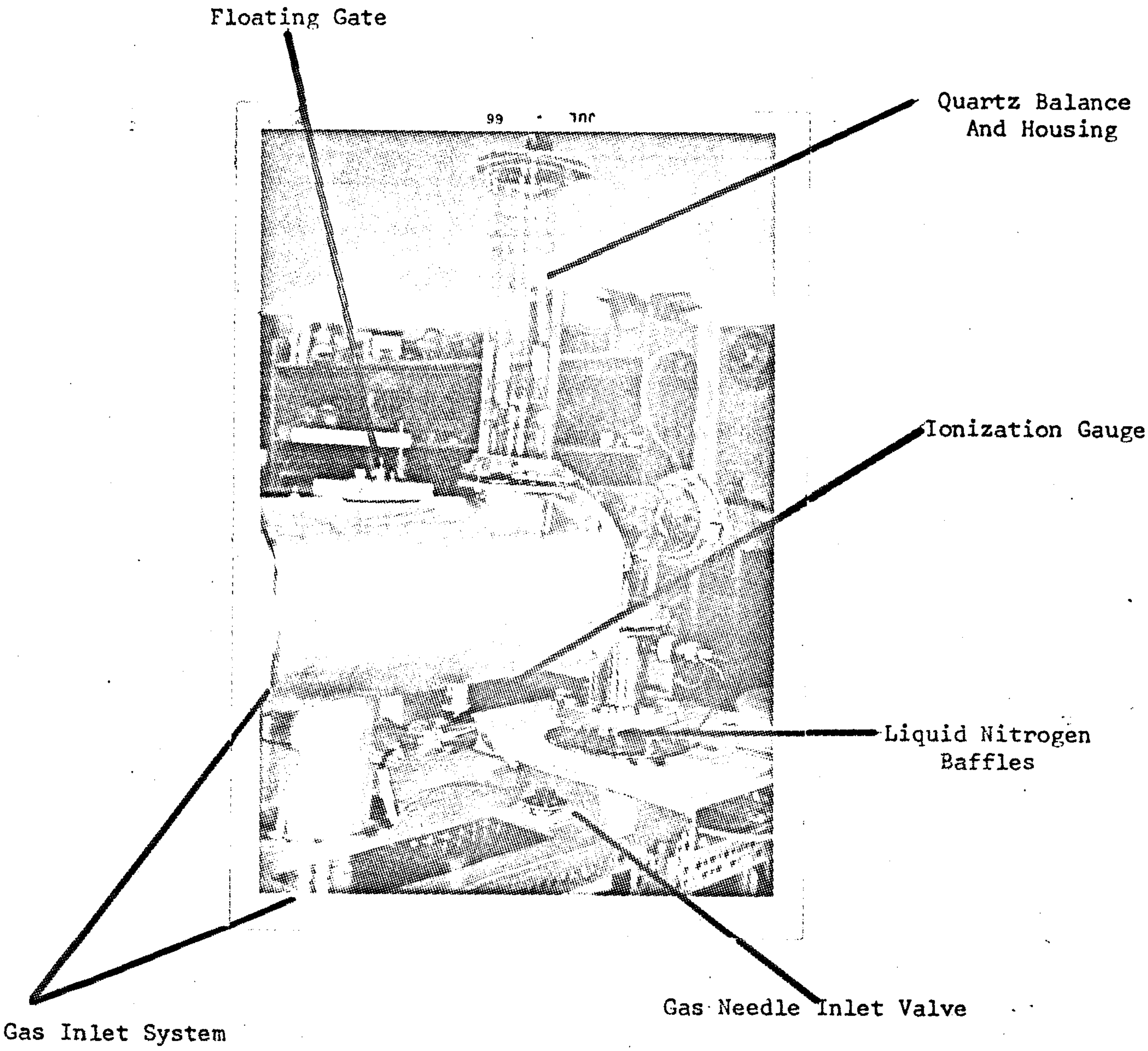
1. Two cold traps attached to the diffusion pumps;
2. An ionization gauge built into the system;
3. A modified liquid nitrogen cold trap for the crystal mount which provides for larger liquid nitrogen reservoir;
4. A new gas inlet, valve and gas-directing nozzle;
5. A floating gate in the beam path for charged particle deflections;
6. A metastable quenching panel;
7. 0 - 5000 Vdc 200 mA power supply;
8. Vane modification for the velocity selector;
9. Flange and 61 cm "double tough" pipe for quartz balance;
10. Quartz balance angle indicator and collimator;
11. Various quartz balances and vanes.

Figure 1 shows the location of these various components on the existing equipment. Figure 2 is a photograph of the quartz balance flange, glass housing and the floating gate. Figure 3 is a full view of the equipment as modified.



NEUTRAL BEAM GENERATOR APPARATUS

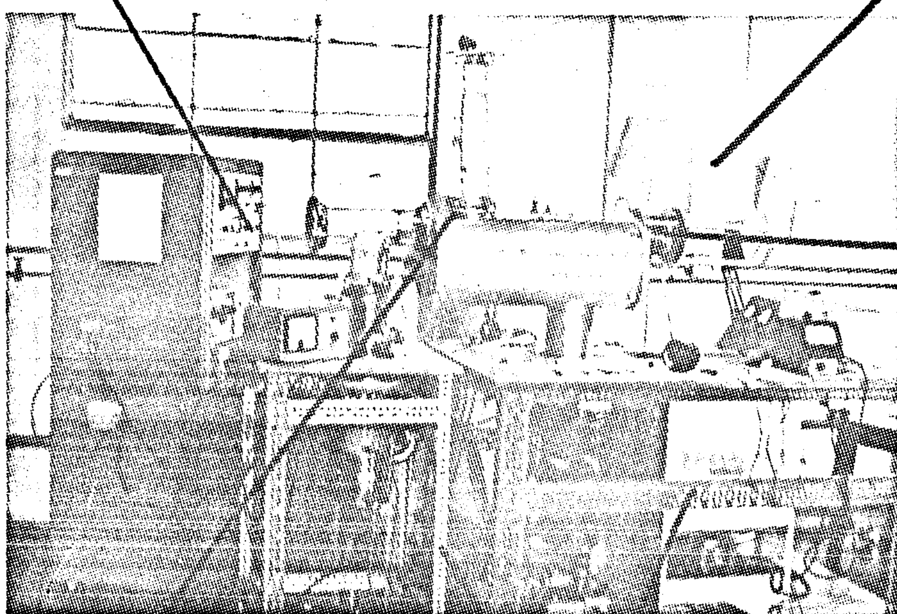
Figure 1.



MODIFIED SYSTEM WITH QUARTZ BALANCE,

FLOATING GATE, AND IONIZATION GAUGE

Figure 2



COMPLETE NEUTRAL BEAM SYSTEM

Figure 3

III. QUARTZ TORSION BALANCES

The quartz balances were constructed of quartz fibers ranging in size from 20 to 50 microns in diameter. One end is attached to a stationary point. The free end of the fiber is attached to a quartz cross bar which serves as a detector element. On one end of the bar is a small metal cone. The cone is placed in the neutral particle beam and is deflected by the beam in proportion to the momentum transfer which takes place. By manually imposing torsion on the quartz fiber to compensate for the cone deflection by the beam, we have a means of measuring the particle energy density. Figure 4 shows schematically the arrangement used and some of the dimensions of specific balances.

The actual targets on the quartz balance were of several designs. Initially, flat metal plates were used but these were discarded when their accuracy could not be insured since the accommodation coefficients are not known. Another design involved the use of what can be called "atom traps". This design was simply a cone constructed from very light aluminum sheet. The cone had an open base approximately 1 cm^2 in area and depth of 1.2 cm. Atoms impinging on this hollow cone would be reflected several times from the surface and give up most of their translational energy before escaping. This would reduce error due to rebound.

Another "atom trap" consisted of a very lightweight porous foam glass. The foam glass surface presented an extremely rough surface. The surface consisted of little cells which provided a trap-mechanism which lowered the probability of rebound. The primary object of the atom trap was to get the atoms to come to thermal equilibrium before leaving the surface. Such a target design could permit a measurement accuracy of 10% from the forces measured.

All of the design developments culminated in a quartz balance which was built with a 20-micron diameter quartz fiber. The balance arm was built in the following manner. A fine 0.010 inch tantalum wire was formed into a rigid circle having a diameter of 6.2 cm. One side of the tantalum ring was attached to the lower end of the quartz fiber. The ring was then suspended in a vertical position and at the extreme horizontal distance on the ring 1-cm^2 plates were attached. The target plates were made of lightweight foam glass which acted as the balance plates on which the neutral beam impacts. The rough-sawed glass surface is believed to capture a greater share of the neutrals and thereby reduces the influence of reflected particles on the measurements. One of the plates has a small metal bar attached to it; this is used to permit magnetic control with a magnet outside the vacuum chamber. Forces could be measured by permitting the torsion balance to rest so that the target was perpendicular to the beam axis. The neutral beam would then be permitted to strike the balance plate and the forces could then be determined as a function of angle of movement. The quartz balance as designed showed a force of one dyne per 9.6° rotation.

Using nitrogen and a thin graphite plate as the bombarding target, many tests were made with the velocity selector. Currents of 50 mA/cm^2 from 500 volts to 5000 volts were used for velocity selector speeds of 1 through 10 x 10^5 cm/sec.

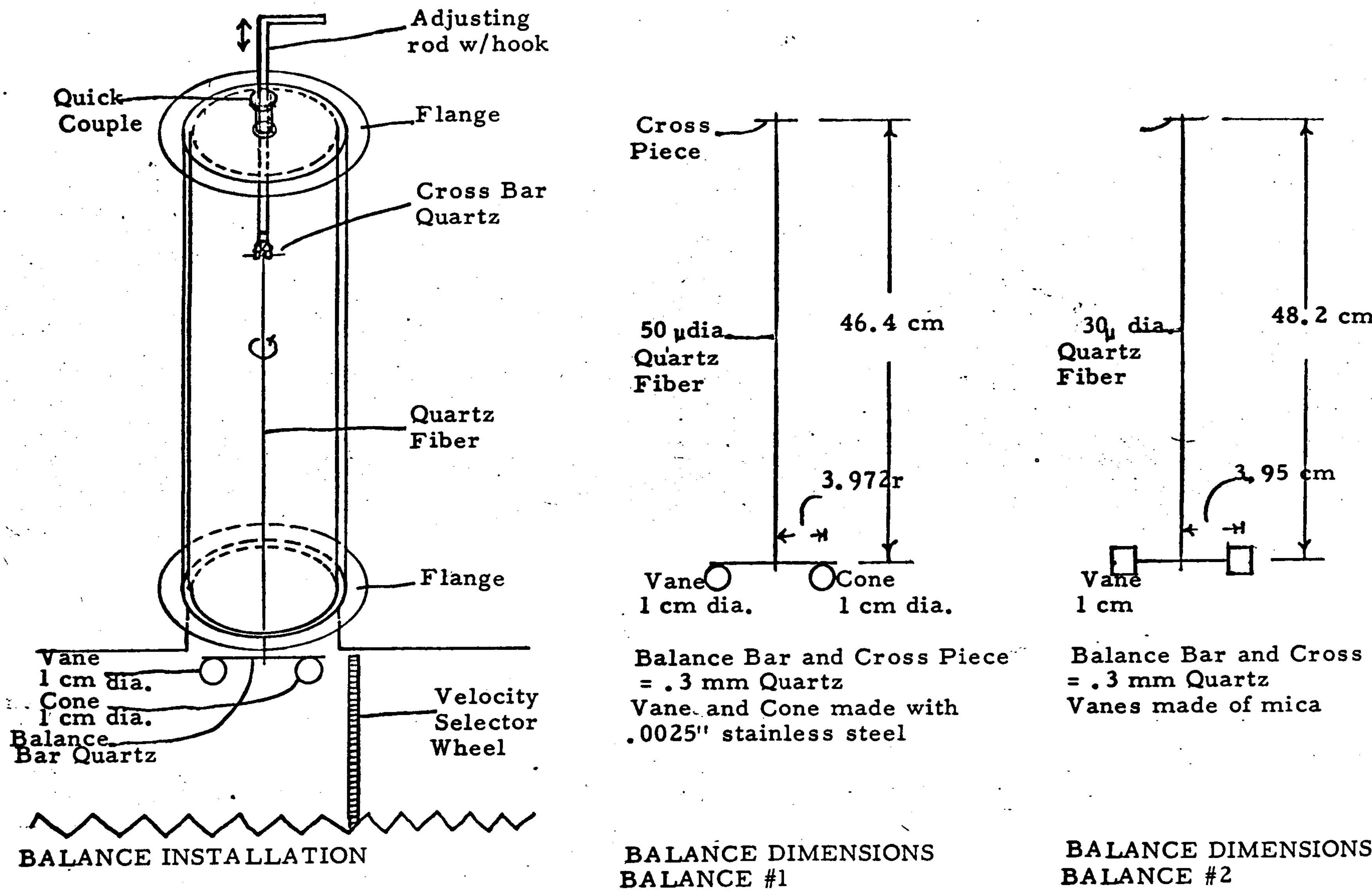


DIAGRAM OF QUARTZ BALANCE CONSTRUCTION

FIGURE 4.

IV. EXPERIMENTAL RESULTS

The initial balance was constructed using a 50 micron quartz fiber and a 0.3 millimeter quartz rod for the balance crossarm, and 0.0025 inch sheet stainless steel to make the 1 x 1 cm vane and 1 cm diameter cone. The quartz parts were epoxied together and the vane and cone were attached to the balance bar. A stainless steel rod with a hook to hold the top of the quartz fiber was inserted through a plate via a quickcouple. This allowed the vertical adjustment as well as a horizontal movement. Please see Figure 4.

A stationary vane, identical to the vanes of the velocity selector, was placed in the system for initial testing of the beam force on the balance. A plexiglass plate was placed at the end of the pyrex tee to allow visual sighting of the balance vanes for accurate alignment. A beam deflection gate was used to control the beam reaching the balance. Assuming no force at the opposite end of the balance bar, the balance equations include:

$$(1) \qquad \phi_{radians} = \frac{P\, r\, \ell\, 64}{\pi\, d^4\, G}$$

$$(2) \qquad s_{cm} = \frac{64\, P\, \ell\, r^2}{G\, \pi\, d^4}$$

$$(3) \qquad P_{gram} = \frac{G\, \pi\, d^4\, s}{64\, \ell\, r^2}$$

where:

ϕ in radians of arm rotation
P in grams force
ℓ in cm - length of fiber
r in cm - arm length
d in cm - fiber diameter
s in cm - distance of arm end movement
G in grams/cm^2 = modulus rigidity

Testing the system as described resulted in measurable forces in the 10^{-2} to 10^{-3} dyne range. To increase sensitivity, it was decided to construct Balance #2 using mica vanes 1 x 1 cm and a reduced quartz fiber of 30 microns diameter. In addition to changing the diameter of the quartz fiber, an increased amount of shielding was added around one end of the balance upon which graduations were provided for measuring movement. The calculations for this construction indicate a balance sensitivity of 10^{-3} dynes per 0.61 cm travel of the arm. Using Balance #2 the following results were obtained:

Voltage	Current	s (cm of vane movement)
1,000	17 mA	2.25 to 2.5 cm
1,500	18 mA	3 to 3.25 cm
2,000	19 mA	3.5 to 4 cm
2,250	19 mA	4.5 to 5.0 cm
2,250	26 mA	6.0 cm

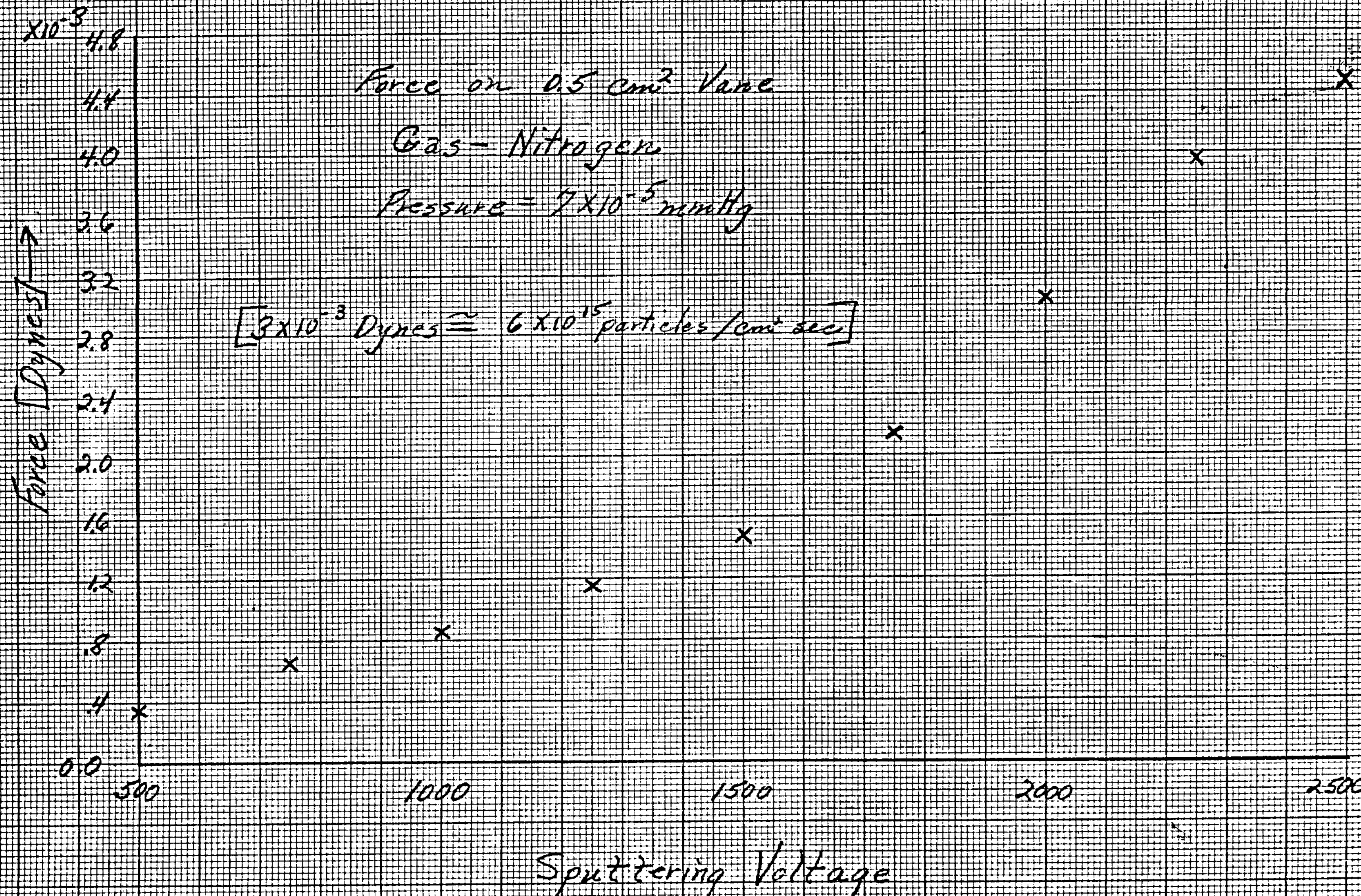
A 6 centimeter vane movement is caused by a force of approximately 10^{-2} dynes. This is about 10^{16} particles/cm^2 sec flux. Plot I shows the results of forces obtained for sputtering energies from 500 volts to 2,500 volts.

A third balance design was constructed with 20 micron quartz fiber and calibrated by the pendulum period method. The 20 micron quartz fiber is 42.5 centimeters long with a 3.7 centimeter radius crossarm. The calibration of this by the equations given above show that a force of 10^{-3} dynes will move the crossarm a distance of 4.78 centimeters. This range of sensitivity is very close to the sensitivity we wish to obtain.

A second calibration was performed by observing the harmonic motion of the torsion balance. The equation for this motion is:

$$\frac{T^1}{\Theta} = -4\pi^2 n^2 I$$

T^1 = restoring force
Θ = angular displacement
n = frequency
I = moment of enertia


Force on 0.5 cm^2 Vane
Gas - Nitrogen
Pressure = 7×10^{-5} mmHg
[3×10^{-3} Dynes $\cong$ 6×10^{15} particles/cm^2 sec]
Force [Dynes]
$\times 10^{-3}$
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
.8
.4
0.0
500
1000
1500
2000
2500
Sputtering Voltage

Plot I

The moment of enertia is changed by adding known weights to the ends of the torsion crossarm and the resulting harmonic motion can then be used to determine the restoring force, T^1.

The problem of electrostatic interference affecting the quartz balance vane was encountered with the 20-micron balance. A shield was placed over the velocity selector motor in an attempt to reduce the electric field produced by the motor armature. On the top of this housing was fastened a magnetic iron plate of approximately 1/4-inch thickness to shield the quartz torsion arms. This arrangement reduced the effect of the motor to a negligible level.

Force measurements were made with one stationary velocity selector vane in the beam path for collimation purposes. The 20 micron torsion balance rotates through 70 to 90 degrees when sputtering voltages of 2000 or 3000 volts are used. These forces indicate a flux of 10^{17} neutrals/cm^2 sec and were so large that it was not reasonable to attempt to make any exact measurements with this balance. When forces from the beam are measured after passage through the velocity selector the flux level drops and a motion of only a few degrees is observed. In these measurements, movement is recorded in centimeters and is proportional to a precalibrated force.

The data obtained with the 20 micron fiber balance was severely limited by the difficulty of taking measurements in the presence of the vibrations caused by the high speed velocity selector. Only limited time was available for the measurements and the data was scattered and cannot be assumed valid without further measurements. Table I shows some of the measurements taken and values obtained.

TABLE I

P. V. (cm/sec)	S. V. (volts, mA)	F (dynes/cm^2)	Flux (n/cm^2 sec)
5×10^5	2500 V, 40 mA	3.14×10^{-4}	2.8×10^{13}
6.2×10^5	5000 V, 40 mA	6.28×10^{-4}	4.34×10^{13}
7×10^5	5000 V, 50 mA	12.1×10^{-4}	7.4×10^{13}
7.4×10^5	3000 V, 12 mA	6.7×10^{-4}	3.8×10^{13}
8×10^5	2700 V, 8 mA	6.9×10^{-4}	3.7×10^{13}
9×10^5	2500 V, 35 mA	5.2×10^{-4}	3×10^{13}

The particle velocity, P. V., was determined by the rotational values of the velocity selector. The sputtering values, S. V., were the bombarding parameters. The force, F, was the value measured by the movement of the 1 cm^2 balance vane. The flux was the calculated number of particles arriving per second at the 1 cm^2 vane, assuming atomic nitrogen and a perfect accommodation of the fast particles. These values were not taken under optimized conditions, but show the initial results of the velocity selected beam.

It was found that large forces are recorded on the quartz balance when the velocity selector was removed with only one stationary selector blade remaining in place between the source and the balance. The electrostatic or vibrational effects associated with the velocity selector that interfere with an accurate measurement of the forces were investigated. Several steps were taken in an attempt to minimize these effects on the quartz balance.

An all metal torsion balance was built and placed in operation in the system. A 0.003 inch tantalum wire was used for the balance and was placed in an identical position to the quartz balance and tested for electrostatic effects. At the lower velocity selector speeds no electrostatic effects were observed. It was, therefore, felt that grounding the balance should be accomplished.

The full torsion balance assembly was platinum plated. This was accomplished with some difficulty because of the fragile nature of the balance. When an electrically grounded balance was put in operation, the electrostatic effect seemed to be eliminated at low speeds, i. e., below 30,000 rpm. At certain velocity speeds above 30,000 rpm the erratic behavior of the balance occurred again. It is now considered that some of the disturbance of the quartz balance is due to harmonics of the vibrational modes produced by the velocity selector motor and rotational motion.

Preliminary measurements show that at 30,000 rpm (7.5×10^5 cm/sec particle velocities) definite and measurable forces are recorded on the balance. It is suspected that the major portion of the sputtered flux may have energies above 6 or 8 eV. We cannot at this time say definitely if this is true; this would indicate that the low energy tail of the number vs. energy curve of the sputtered particles may be too low to produce dense beams below 5 eV. Special techniques to lower the energy of the sputtered beam are feasible, however.

An abstract entitled, "Monatomic Oxygen and Nitrogen Beam Apparatus for the 1 to 10 eV Range," was written in anticipation of submittal of the paper to the Fifth International Conference on the Physics of Electronic and Atomic Collision. This paper has been attached as an appendix.

V. SUMMARY AND RECOMMENDATIONS

The experimental effort to measure the total flux densities by the use of torsion balance momentum transfer detectors was only partially successful due to unexpected problems and instabilities of the torsion balance. Fairly accurate measurements were obtained for the total beam which included the total spectrum of velocities. When subsequent measurements were made using the velocity selector, only indications of the presence of forces were obtained, but no reliable data can be reported.

It is believed that the most effective way to continue this work and determine the total parameters of the system requires the use of a mass spectrometer. The spectrometer should be calibrated with ions produced at the source and accelerated through the velocity selector; thus, providing velocity, mass, and flux density determinations.

APPENDIX

MONATOMIC OXYGEN AND NITROGEN BEAM APPARATUS

for the

1 to 10 eV RANGE

Dense beams, composed primarily of monatomic oxygen and nitrogen, are being produced at energies from 1 to 10 eV. A continuous beam of energetic atoms is generated by sputtering condensed layers of gases from an in vacuo cold finger surface. The sputtered atom beam is passed through a velocity selector to provide a sharp velocity spectrum. Resultant beam fluxes of 10^{15} atoms/cm^2 sec are obtained over an area of 2 cm^2.

The apparatus is designed with a copper single crystal, crystallographically oriented so that the close-packed atom rows are aligned parallel to the desired beam direction. The crystalline substrate causes the condensing gas to form, at least in part, an epitaxial layer over the crystal. Subsequent ion bombardment of these layers results in preferential ejection* of atoms directed along the close-packed lattice rows. The sputtered atoms have energies one and two orders of magnitude above thermal. The ions for sputtering are drawn from a plasma generated by r. f. field coils placed about the glass chamber. Negative potentials between 500 and 4000 volts are applied to the crystal and the positive ions are drawn directly to the crystal surface. The gas for the plasma and condensed layer is emitted by a needle valve into the first chamber where the pressure is maintained at $\sim$4 to 6 x 10^{-4} mm Hg.

The condensed atoms which are sputtered from the crystal surface are ejected axially through a 1 x 2 cm copper tube. The tube is placed within one or three centimeters from the crystal surface. The tube suppresses the plasma from the path along which the fast neutrals traverse towards the detector. This was found necessary because charge-exchange processes in the plasma were efficient in detaching electrons from the fast neutrals.

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* Several authors have published results including: G. K. Wehner, J. Appl. Phys., <u>25</u>, 270 (1954); Phys. Rev., <u>114</u>, 1270 (1959); and V. I. Veksler, Soviet Phys. (JETP), <u>11</u>, 235 (1960).

The plasma-neutral interactions also produce excited states, and the spacing between the crystal and suppressing tube can be varied to limit these effects.

The sputtered neutrals stream next into the velocity selector chamber. Velocities can be selected by varying the rotational speed of the chopper. The velocity selector chamber is differentially pumped by diffusion pumping at a rate of 700 liters/sec. Those particles which are deflected by the chopper, as well as the thermals which diffuse through the 1 x 2 cm tube, are removed by this first pump. The fast neutrals which have the proper velocity to pass through the selector enter a 1 x 2 cm slot to the final chamber. This chamber is pumped by a second 700 liter/sec oil diffusion pump. The pressure of this region during beam operation remains at 5 to 6×10^{-6} mm Hg.

The beam is monitored by a cross-electron type detector housed in the tube extending into the velocity selector chamber. The detector measures the number-density drom which the calculated flux density of the beam is determined. The energy of the fast ions is determined by retardation potential measurements. Quartz torsion balances are used to determine the absolute energy-density of the beam.

The beam particles are predominately the atomic species of oxygen and nitrogen. A study of excited states indicates the presence of a substantial population of metastables in the beam. Future refinement and use of the beam is planned for investigating collision processes in the 1 to 10 eV energy range.